

## **Bubble Growth and Rise in Gassy Sediments**

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### **LONG-TERM GOALS**

Our long term goal is a quantitative, mechanistic and predictive understanding of the growth and rise of bubbles and (eventually) bubble populations in marine sediments. We believe this information can be used to improve and test acoustic backscatter models for sediments, better understand the ebullitive flux of methane, an important “greenhouse gas”, to the atmosphere, and the release of volatile pollutants.

### **OBJECTIVES**

The overall objective of our work is to understand bubble growth and rise in natural marine sediments. In the first phase of our study we demonstrated that bubbles typically grow and rise in sediments by the mechanism of fracture. In the second phase we plan to further validate our results from phase one, expand our experimental observations and models of bubble growth to include a broader range of natural marine sediments, and parameterize bubble rise and particularly rise by the mechanism of fracture in natural and surrogate sediment materials.

### **APPROACH**

We conduct coordinated laboratory, field and modeling research to achieve our objectives. The laboratory work (directed by Bruce Johnson and assisted by Regine Maass) aims to: 1) validate our fracture model for bubble growth, 2) determine how bubbles rise in sediments through studies of surrogate and natural sediment samples and 3) develop a probe for laboratory and field use to measure the sediment properties that control bubble growth and rise, e.g., for fracture these properties are Young’s modulus,  $E$ , and the critical stress intensity factor,  $K_{Ic}$ . In field work (directed by Bruce Johnson and Bernard Boudreau and assisted by Regine Maass), we will measure the mechanical properties that control bubble growth and rise, e.g.,  $E$  and  $K_{Ic}$ , in a broad range of sediment types and will relate these measurement results to other sediment properties, e.g., organic content, salinity and porosity. Modeling (directed by Bernard Boudreau) will focus on understanding and describing

laboratory and field results, and will seek to identify the minimum subset of variables that will predict bubble growth and rise in natural marine sediments.

## **WORK COMPLETED**

The project has published three papers Boudreau et al. (2001), Johnson et al. (2002) and Gardiner et al. (2002), and has submitted another (Gardiner et al., submitted). In the first year of phase 2 of our study (beginning in late December 2001), we have: 1) extended the interpretation of our laboratory gas-injection studies by determining the value of  $K_{Ic}$  for each fracture peak in the record of bubble growth, and 2) fabricated and tested three different probes for measuring the properties that determine fracture behavior in sediments, one of which can now be used both in the laboratory and in the field.

## **RESULTS**

### *1) Laboratory and Field Experiments*

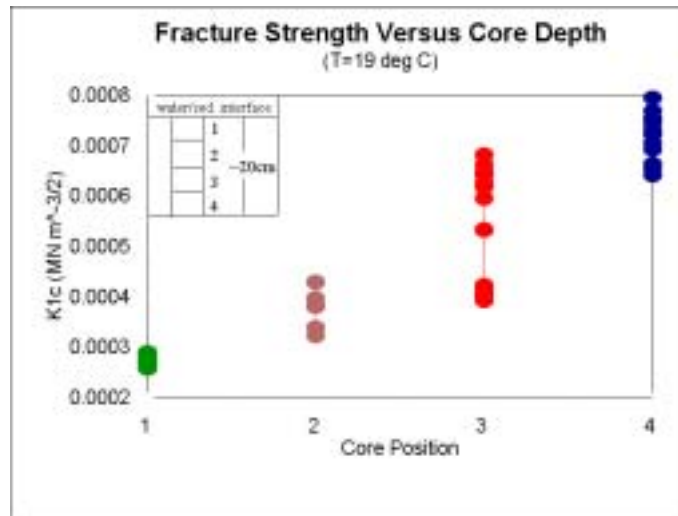
In the first phase of our study we measured pressure during injection of small amounts of air into natural and surrogate sediment materials. X-ray and visual results showed that the bubbles that formed in most of our samples grew in the shape of disks with principle axes oriented vertically/sub vertically. We subsequently demonstrated that the process is consistent with the mechanism of bubble growth by fracture. We then showed that our results could be described by “linear elastic fracture mechanics”, or LEFM. In this, the simplest description of fracture, the geotechnical properties that fully determine fracture strength and the size and shape of resulting cracks are the ‘critical stress intensity factor’,  $K_{Ic}$ , and Young’s modulus,  $E$ . We then determined the magnitudes of  $K_{Ic}$  and  $E$  for samples collected at our study site in Cole Harbor, Nova Scotia and reported these results in the Journal of Marine Geology (2002). As far as we are able to determine, ours are the first published measurements of  $K_{Ic}$  to be reported for marine sediments.

#### *Interpretation of Fracture Data:*

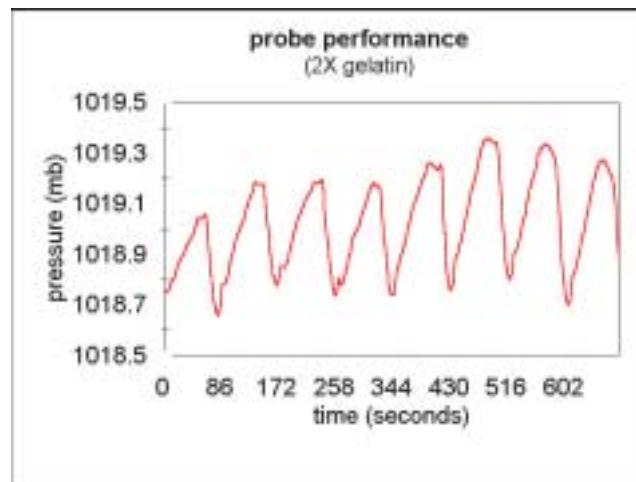
For the results reported in the Journal of Marine Geology we determined  $K_{Ic}$  from the plot of log critical pressure (for fracture) versus log bubble volume. This method can only be used when the slope of such a plot approaches  $-1/5$ . We have subsequently determined that  $K_{Ic}$  can also be calculated from each fracture peak in the record of bubble growth, and consequently we have been able to further analyze results from our bubble injection experiments. Some of these new results are shown in figure 1 which describes how  $K_{Ic}$  varies with depth in a sediment core from our study site. The increase in  $K_{Ic}$  with depth in the core might be expected to be the result of physical and chemical changes in sediment following burial and may be one reason that bubbles grow in a vertical orientation.

#### *Fracture Probe Development:*

Our present methods for determining  $K_{Ic}$  and  $E$  are not suitable for field measurements nor do they provide sufficient detail to understand the variability of these properties on desired length scales. We therefore have begun developing a



**Figure 1: Plot showing how the critical stress intensity factor,  $K_{Ic}$  varies as a function of depth in a sediment core from Cole Harbor, Nova Scotia. [The value of  $K_{Ic}$  increases approximately linearly from about  $3 \times 10^{-4} \text{ MN m}^{-3/2}$  in the top 5 cm to to about  $7 \times 10^{-4} \text{ MN m}^{-3/2}$  in the depth interval from 15 to 20 cm below the sediment /water inteface]**



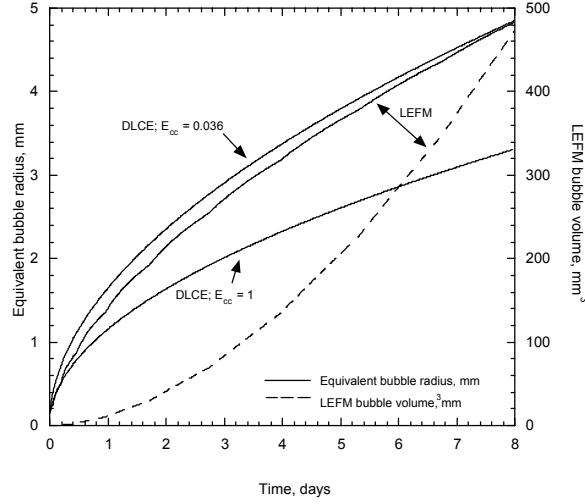
**Figure 2: Results from slow translation of one prototype fracture probe into a sediment sample. [the results show a series of peaks that indicate fracture and crack propagation].**

fracture probe that can be used both for laboratory and field measurements. One set of results showing the peaks at which fracture occurs appears in figure 2. We anticipate interpreting results such as these in terms of propagation of a deep edge crack.

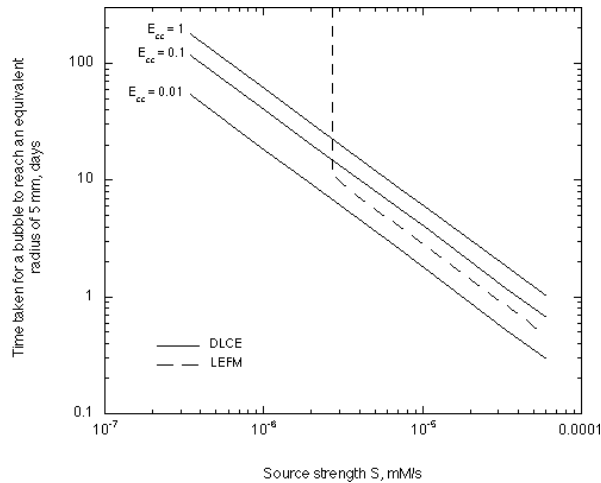
## 2) Modelling Discoidal Bubble Growth

Our experiments (described above and in Johnson et al., 2002) show that disc-shaped methane bubbles in marine sediments result from growth in a medium that elastically resists expansion of the bubbles

and yields by fracture. We have modeled this process to obtain estimates of growth times, using a reaction-diffusion model (in the oblate spheroidal coordinate system) that is coupled to a linear elastic fracture model (LEFM). For comparison we have also modeled the growth of a constant eccentricity bubble in a non-resistant medium, which includes the case of a spherical bubble as treated earlier in Boudreau et al. (2001).



**Figure 3. Bubble growth with time for a bubble in a fracturing medium (LEFM) and two constant eccentricity bubbles in a non-resistant medium (DLCE). The model parameters are those for the Cape Lookout Bight site (Boudreau et al., 2001a); in addition the two fracture parameters, Young's modulus and the critical stress intensity factor, are set to value of  $E = 1.4 \times 10^5 \text{ Nm}^2$  and  $K_{IC} = 300 \text{ N/m}^{3/2}$  determined by Johnson et al. (2002).**



**Figure 4. A plot of the effect of source strength on bubble growth times for the fracture-growth (LEFM) model and for various bubble constant eccentricities under the no-resistance (DLCE) model. Note that the LEFM model predicts that at low source strength bubbles will cease to grow, i.e., bubble-growth arrestation, a phenomenon we cannot find documented in the scientific literature.**

Discoidal bubbles in sediments that obey LEFM grow much faster than spherical bubbles, i.e., 2-4 fold faster (Fig. 3), become more eccentric with time (aspect ratios falling from 0.3 to 0.03 over 8 days of growth), and their growth is not continuous, but punctuated by fracture events. Furthermore, under some conditions, the LEFM model predicts that bubble growth can become arrested (Fig. 4), which is not possible for a bubble in a non-resistant medium, even for non-spherical bubbles. Cessation of growth occurs when the dissolved gas concentration gradient near the bubble surface disappears due to the increase in bubble gas pressure needed to overcoming sediment elasticity. This type of cessation of growth is a new phenomenon, never described in the scientific literature.

## **IMPACT/APPLICATIONS**

Bubbles in sediments can seriously compromise acoustic sensing of naval mines, destabilize structures that rest on the bottom, and transport methane, a potent greenhouse gas, to the atmosphere. Thus, understanding bubble formation and movement in sediments constitutes an important practical and scientific problem. Our findings will provide information that may be used in prediction of: bubble populations and residence times in sediments, mechanical stability of the seabed, rates of methane flux to the atmosphere and acoustic transmission.

## **TRANSITIONS**

None.

## **RELATED PROJECTS**

None as yet! We are interested in and looking for partners to share our research results.

## **PUBLICATIONS**

Boudreau, B.P., Gardiner, B., and Johnson, B. (2001) Rate of growth of isolated bubbles in sediments with a distributed diagenetic source of methane. *Limnology and Oceanography* 46, 616-622. (see also the Erratum in the same issue)

Gardiner, B.S., Boudreau, B.P. and Johnson, B.D. (in press) Growth of disk-shaped bubbles in sediments by fracture. *Geochimica et Cosmochimica Acta* (Accepted April 2002).

Johnson, B., Boudreau, B.P., Gardiner, B. and Maass, R. (2002) Mechanical response of sediments to bubble growth. *Marine Geology* 187, 347-363.

Gardiner, B.S., Boudreau, B.P. and Johnson, B.D. Diffusion-limited growth of a disk-shaped bubble. *Applied Mathematical Modelling*. (Submitted Dec. 2001)